# Advanced space concepts bio-inspired by spider attaching mechanisms and plant roots

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**Abstract**

Performed studies show that a biomimetic approach has potential to face challenges and difficulties of modern space engineering design. Key areas of bio-inspired space applications have been identified and classified. In this paper, the concepts of spider-inspired attaching mechanisms and soil probing capabilities of plant roots are proposed for the exploration of inhomogeneous, unstructured and unknown space environments.

## 1. Introduction

Aiming at outlining the benefits of a biomimetic approach for possible future developments of space technology, promising key areas have been identified and assessments of biomimetics for space system design carried out [1, 2]. There is a demand for systems of high robustness, reliability, autonomy and adaptation in order to cope with the harsh constraints and uncertainty imposed by a multiform space environment. Evolution has tailored these critical needs for a diversity of terrestrial organisms. In the following, two bio-inspired concepts are suggested: spider attaching mechanism and path-finding capabilities of plant roots.

The first concept concerns spiders which have conquered nearly all habitats on Earth. In hot and dry deserts, swampy rainforests, even underwater, they are facing most unfavourable conditions. One mayor key of success is attributed to spiders' locomotion and attachment apparatus. They climb on vertical surfaces, upside-down, build webs and agilely walk on them; some jump several times their body length and balloon on a strand of silk.

Current spider-inspired prototypes, mainly based on macroscopic observations of the animal's design, are not competitive; however, research on spider strategies is expected to lead to innovative solutions that meet the strict requirements to be integrated in future space payloads.

The second concept concerns plant-inspired engineering systems. From sub-mm scale to gigantic sequoias, plants exhibit remarkable diversity. Here, we suggest plant roots as smart and adaptive path-finding mechanisms, essential for plants' survival as plants do not show active locomotion. Mimicking their holistic design and mechanisms of growth could be a prospective starting point for the design of autonomous, self-optimising systems suitable for planetary exploration.

## 2. Spider-inspired locomotion and attaching mechanisms

Under stability aspects, octapedal gaits apparently yield no gain; however, while walking, spiders aptly use legs as sensors (feelers, contact-chemo-sensing) and manipulators (operate webs, seize prey, dig burrows). Besides, in emergencies, individual legs can be dropped and gaits readjusted. Spiders exhibit a variety of locomotive abilities; some even march sideways, backwards or stride on water.

Since generally their feeble vision is restricted to vague near-field cognition, spiders rely on highly sensitive mechanoreceptors. Proprioceptive joint receptors, chemical probing and humidity sensors complete a sensory network allowing agile locomotion over a large variety of terrains [3].

The attachment apparatus at the tarsal tip of each leg consists of two combined large claws and species-specific ventrally located micro-structured hairy attachment pads. The claws grip on rough surfaces, whereas the hairs cling on smooth ones. Web spiders own an additional middle hook to grasp the silk thread. Web-less hunting spiders typically carry sophisticated bunches of scopulae hairs underneath the claws that permit the animal moving upside-down at polished glass panes due to its microscopic organisation where the triangularly broadened distal setule ends constitute the direct contact to substrates [3-5].

Although not completely verified yet, there’s much evidence that the setule grip is mainly achieved by van-der-Waals forces mediated through an increased number of setule-substrate contact points, assisted by the soft cuticule matrix clinging tightly to substrate contours [4-6]. Spider adhesion is superior to insects’ although the latter is supported by sticky secretions [5].

Geckos [6] and flies [5] detach by peeling their pads to actively break up the van-der-Waals forces. For spiders, it is not yet sure how they unfasten. The scopulae might be hydraulically detached by gradually decreasing the hemolymph pressure [3]; also anisotropy effects could be involved.

- **Possible space applications**

Biomorphic spider-devices are relevant for space scenarios of surface and web mobility. Spider locomotion based on dry adhesion deals with any kind of unstructured surfaces, regardless texture and specific conditions, also in space vacuum [6].

These assets give rise to advanced space applications such as intra- and extravehicular inspection, monitoring and maintenance of spacecraft, space stations, or satellites, where conventional methods of hold like suction or electromagnetism fail. In particular autonomous robotic inspections of critical subsystems for environment control, life support, or other hazardous environments, release astronauts from perilous manoeuvres. Equipped with wireless communications units, collaborative spider agents patrolling inner and outer hulls could either directly fix small defects or execute directives received from control stations.

Spider-robots for space body exploration would overcome known limitations of wheeled rovers (getting stuck or crash). Embedded sensor probe systems would allow safe in-situ pre-examination and collection of suitable samples – critical aspects of exobiology missions. Also other tools might be leveraged by spiders’ peculiar characteristics for the improvement of, e.g., astronaut security systems, gloves with high grasp and haptic feedback, non-destructive grippers, etc.

In recent years, space agencies have driven much research towards large deployable space structures like energy-harvesting solar sails, antenna arrays or debris removal [7]; shape and position of expanded membranes can be actively controlled by small corner satellites or thrusters (Fig. 1).

Fig. 1: Artist view of a Furoshiki membrane tensioned by corner satellites.(Adjusted from [7])

Large structures (up to 1 $km^2$ in size) can conveniently be assembled in situ, directly in space. An efficient way is using autonomous agents that move on previously deployed net-like frames. In this context, biological folding and unfolding systems have been studied [2], and first basic deployment tests in space have fruitfully demonstrated their feasibility [8].

Fig. 2 depicts a sketch of a triangular space net where robots crawl out of the centralized mother satellite on the net towards the small daughter satellites at the corners. Moving on waving nets in microgravity is very demanding since in absence of gravity, there's no force to push the robot to the mesh. Thus, robots can be designed using a complex subsidiary wheel configuration to be kept attached [7]. This set-up looks promising for robots interacting with nets like web spiders do.

Fig. 2: Conceptual view of a deployed space web and robots moving on it [7].

More applications of controlled passive adherence are assessable on earth since the boundary conditions are by far not as stringent as those in space. Dry adhesion is expected to significantly enrich many systems, e.g., cleaning and inspection of walls, pipes, oil tanks or nuclear plants [6]. First steps towards reusable sticky tapes have been done and early robotic applications [6, 9] presented. Especially for delicate substrates, additional issues such as non-destructive and non-contaminating reusability need to be addressed.

## 3. Plant root strategies

Subterranean roots anchor plants and actively explore soils to feed plants with mineral nutrients and water. They are robust and self-replicating. Dependent on the mechanical impedance of the soil [10], a ramifying primary root and/or a widespread fibrous system forms adapting to the local conditions.

The penetration strategies of roots are exciting biological examples of high-performance navigation through soil. To maximise the plant's fitness function, root growth is adaptively directed towards areas of least physical resistance. Mainly dictated by tropic stimuli, superimposed by soil mechanics, roots grow in two apical zones: a zone of cell division (mitosis) in the meristem and shortly back from the apex in the elongation zone. The driving force for elongation is generated by osmotic pressure due to water influx into the cells which, during the process of growth, overcomes external pressure and friction, while soil particles are compacted or displaced.

- **Possible space applications**

Smart path-finding engineered roots are suggested for exploration and exobiology missions with the objective of characterizing biological and geophysical environments while identifying hazards for future human missions. Bio-inspired subsurface drills [11] are promising for collecting and analysing soil samples to detect microfossils or signs of water to investigate whether life ever arose on that object. Compared to the methods currently used, root penetrators might be favourable in terms of low power consumption, robustness, and smart avoidance of potential malign threats, features that are crucial for autonomous and safe exploration of unpredictable environments. Further incentives are given by the way roots of neighbouring plants communicate with each other, or with other soil organisms, and how they deal with evident problems such as abrasion, friction, and heat generation. In this scenario, drilling roots actively explore soils while looking for gradients of water, minerals, or hints of metabolic activity. Theoretically, local 3-dimensional subsurface maps could be generated.

In possible combination with spider-inspired attachment, planetary landers could be firmly secured to any ground by deeply penetrating or widely branching surface roots. The mechano-sensoric attachment system would then start analysing surface or subsurface conditions and collecting data regarding geothermal, volcanic or seismic activities. In Situ Resources Utilisation (ISRU) scenarios, the possibilities of energy storage, recovery or extraction from regolith soil, might be addressed by root-inspired systems. Detailed studies are needed to assess possible realistic advantages in these scenarios.

## 4. Conclusion

This paper focuses on the impact of biomimetic research for advanced space systems by presenting two concepts: spider attaching mechanism and soil exploration of plant roots.
Passive operations and negligible dependence on substrate texture and environmental effects challenge actual solutions for space systems. Adhesive prototypes based on dry stiction have shown a certain level of technology readiness and confirmed that small robotic systems can climb smooth, almost vertical walls [6, 9]. However, robustness and reliability are still of main concern. A studied technological alternative relies on carbon nanotubes [12] that should allow extremely high packing densities for high adhesive forces and adhesion to mass ratio. Being good thermal and electrical conductors, appropriate electrostatic charging might assist adhesion and/or probably might allow controlled detachment, promoting extended lifetime and reliability. Material selection is of prime importance in space applications. Significant degradation effects occur due to long duration exposure to energetic particles, solar radiation flux, atomic oxygen, and thermal cycling; also out-gassing effects arise. By adequate treatment and protection, resistance to some degrading agents can be achieved, mainly depending on the mission-specific constraints. Some perfluorinated polymers, polyimides, epoxies and silicones are found to be suited.

Our second proposal concerns the adaptive path-finding and guiding abilities of plant roots. With minimal energy and external control efforts, roots penetrate soils towards the most favourable survival conditions.

While artificial root systems will operate in the shielding soil of celestial bodies, they are not directly exposed to degrading cosmic agents, but their possible functional design is extremely demanding. A main issue is to define reliable and controllable mechanisms mimicking the features of growing roots. Selected materials must allow both adaptive and mechanically strong solutions that are resistant to frictional heat and abrasion. A multi-segmented system could be a promising starting point.

Some electroactive polymers might be suitable in terms of actuator/sensor integration although most smart materials are still in their infancy. Shape memory alloys could also be considered as actuation speed is generally not a constraint. At present time, to the best of the authors' knowledge, no such an artificial system has been proposed for space use.

In the scope of upcoming astrobiology missions, we believe that biomimetic concepts like those presented will enrich the future progress of space technology. On a long-term basis, main fields of application concern autonomous exploratory missions aimed at probing unknown environments for subsequent human exploration of space bodies.

## 5. References

[1] C. Menon, M. Ayre & A. Ellery. Biomimetics - A new approach for space systems design. ESA Bulletin 125, 20-26, 2006.
[2] M. Ayre & N. Lan. Biomimetic Engineering for Space Applications. ESA SP-127, 2006.
[3] R.F. Foelix. Biology of Spiders. 2nd ed., Oxford University Press, New York, 1996.
[4] A.B. Kesel, A. Martin & T. Seidl. Getting a grip on spider attachment: an AFM approach to microstructure adhesion in arthropods. Smart Mater. Struct. 13, 512-518, 2004.
[5] S.N. Gorb. Uncovering Insect Stickiness: Structure and Properties of Hairy Attachment Devices. Am. Entomologist 50, 31-35, 2005.
[6] C. Menon & M. Sitti. Biomimetic climbing robots designed by reversing engineering ideas from gecko locomotion capabilities. J. of Bionic Eng., 2006 (to appear).
[7] N. Kaya, M. Iwashita, S. Nakasuka, L. Summerer & J. Mankins. Crawling robots on large web in rocket experiment on Furoshiki deployment. 55th IAC, Vancouver, 2004.
[8] G. Tibert, M. Gärdsback & D. Izzo. Deployment of Space Webs. 8th Gossamer Spacecraft Forum, Waikiki, 2007 (in prep.).
[9] K. A. Daltorio, S. Gorb, A. Peressadko, A.D. Horchler, R.E. Ritzmann & R.D. Quinn. A Robot that Climbs Walls using Micro-structured Polymer Feet. 8th CLAWAR, London, 2005.
[10] L.J. Clark, W.R. Whalley & P.B. Barraclough. How do roots penetrate strong soil?. Plant and Soil 255, 93-104, 2003.
[11] C. Menon, J.F.V.Vincent, N. Lan, L. Bilhaut, A. Ellery, Y. Gao, D. Zangani, S. Carosio, C. Manning, M. Jaddou & S. Eckersley. Bio-inspired micro-drills for future planetary exploration. Proc. of CANEUS, Toulouse, France, 2006.
[12] G.M. Spinks & G.G. Wallace. Carbon Nanotube Actuators. In: Electroactive Polymer (EAP) Actuators as Artificial Muscles. Ed. Y. Bar-Cohen, SPIE Bellingham, Washington, 2001.